The UNIVERSITY of TENNESSEE

Department of Physics

Knoxville, Tennessee

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FINAL REPORT

of

The University of Tennessee Department of Physics
Knoxville, Tennessee

on

STUDY OF PNEUMATIC ELEMENTS FOR RADIATION DETECTORS

Work Performed Under Contract NONR-811(01)

With

OFFICE OF NAVAL RESEARCH

1 May 1954

Report by: John D. Trimmer, Principal Investigator

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Study of Pneumatic Elements for Radiation Detectors

FINAL REPORT -- CONTRACT NONR-811(01)

I. Project Objectives

This is the Final Report on a project initiated April 1, 1952, originally for a one-year period, but then extended to cover the second year, ending March 31, 1954. The primary Task Order called for experimental and theoretical survey studies of known means of numerically indicating information, directed towards "attempts to adapt or devise superior means of indicating on portable radiation detectors". The first year's survey work[1] directed attention to possible use of pneumatic elements in radiation detectors.

A proposal for extension of the contract to cover a second year was therefore formulated, suggesting a limited continuation of survey study, but emphasizing primarily the possibilities of pneumatic elements. These possibilities are two-fold: the indirect pneumatic effect, in which radiation is first transduced to an electrical effect, which the pneumatic system is then used to indicate; and the direct pneumatic effect, in which the radiation exerts directly a measureable effect on a pneumatic parameter, such as temperature, pressure, or viscosity.

II. Size of Project Effort

During the year ending March 31, 1954 the project was given one-fourth time by the principal investigator and by Associate Professor James W. White. A student assistant (Mr. Ted Lundy) was employed full-time through the summer months, and on an hourly part-time basis during the academic term. Machine shop time was contributed by The University of Tennessee Physics Department.

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(1) Numbered references are given in the Bibliography.

III. Summary of Project Accomplishment

The major portion of experimental work was devoted to the indirect pneumatic effect. This evolved into a study of pneumatic methods of measuring small forces--i.e., design of a sensitive force-pressure transducer. Such a transducer, in conjunction with a more or less conventional small-current electrical meter movement (i.e., a current-force transducer) would constitute a pneumatic microammeter. The net result of this study is that sensitivity (and perhaps other specifications of ruggedness, stability, etc.) achievable in a pneumatic microammeter appear inadequate for direct, battery-less indication in a portable radiation detector. However, results obtained with the force-pressure transducer are believed to be new, and of value in some fields of instrumentation, such as pneumatic weighing. A patent application has therefore been initiated on the force-pressure transducer.

The general problem of optimum design of a pneumatic force-pressure transducer has been touched only very lightly. A rather wide field of investigation appears to be open here, with good promise of valuable practical developments.

Direct pneumatic effects of radiation have been given much less attention. This does not mean that ultimate possibilities in this direction are evaluated so much lower; resources of time and manpower were simply not available for decisive exploration of such possibilities.

In addition to the rather specific work relating to portable radiation detectors, more general studies in instrumentation[(2),(3)] have received collateral support from the project.

IV. Radiation Detection by Indirect Pneumatic Effect

Radiation detectors often include some auxiliary store of energy, such as electrical batteries. For portable electronic radiation detectors, batteries at one time constituted a significant fraction of weight and volume of the total instrument. Development of miniature vacuum tubes (and even more,

the present active development of transitors) has greatly reduced current requirements, and new developments in miniature batteries have also been made. So it has been possible progressively to reduce the total weight and size of battery-operated radiation detectors. Perhaps a more serious problem is presented by battery shelf-life. This is particularly embarrassing for civil defense use, where a regular inspection of battery complement might be hard to establish.

It is therefore of some interest to devise battery-less detectors, in which all required energy is furnished either by the radiation itself or by the person using the instrument. For example, if one assumes the existence of a transducer, such as the Ohmart cell[(4)], which converts radiation to an electrical current without aid of batteries, one might then attempt either to indicate the current directly on a super-sensitive meter, or to find some means of amplifying the currect other than electronic, battery-operated amplifiers. A possible scheme of amplifying the effect of an electric current is the combination of some more or less conventional meter movement, to convert current into force, with a pneumatic force amplifier. Power for the pneumatic amplifier could be furnished by means of manual pumping by the instrument user.

Industrial pneumatic instrumentation has long made use of devices in which a small jet of air flowing from a nozzle impinges on a baffle, which is movable with respect to the nozzle opening. Our primary aim was to study such nozzle-baffle configurations for measurement of small forces.

Our work on these possibilities is therefore reported here in the following order: first, force measurement with a single flat nozzle and flat baffle, the configuration which we studied most intensively; second, force measurement with other geometrical configurations; third, our conclusions on force measurement by pneumatic means; and fourth, our conclusions on portable radiation detectors using the pneumatic force amplifier.

The Single Flat-Nozzle Flat-Baffle Configuration. Details of this method are given in Appendix A, with some simple theoretical interpretation. Results are presented here in the following terms: the force F applied to a small movable baffle is converted into pressure p, the transducer being supplied with air at regulated pressure of some fixed value between zero and 20 psi g.

A typical curve of pressure versus force is shown in Fig. 1. Variation of separation x is also indicated. Both at small and at large x the force is positive (repulsive). Over a certain range of separation the force is negative (attractive), and reaches an extreme, $-F_m$, at the point marked A, corresponding to an x-value which we may designate x_m. At A the slope dp/dF is infinite, meaning that a very small positive force would cause a noticeable pressure change. Operation of the system on the branch AB would be unstable, since positive displacement results in more positive force. Operation on the branch AC, where negative displacement corresponds to increasing force, would be stable. Over this range the slope of pressure with respect to force is positive, of magnitude very large near A and decreasing toward C.

In practical application one would have to insure stability by limiting the separation to something less than x_m, thus ruling out the ultimate maximum of sensitivity corresponding to point A. In tests made with the baffle mounted on a flat-strip spring, cantilever-suspended, a slope of 5×10^{-4} psi per milligram was observed with good linearity and fair stability over the range from zero up to 100 milligrams. (Supply pressure: 10 psi; orifice diameter: 0.0145"; nozzle diameter: 0.025"; beryllium copper strip, 0.013 cm x 2.3 cm x 16.5 cm.) The sensitivity corresponds for one milligram to more than 0.01 ins. H_2O; this is easily read, for example, on a Model 215 Dwyer inclined manometer, which has a five-inch scale for the range 0.10-0-0.15 ins. H_2O. We therefore feel that useful pneumatic devices for weighing of milligram quantities might well be built along the above lines.

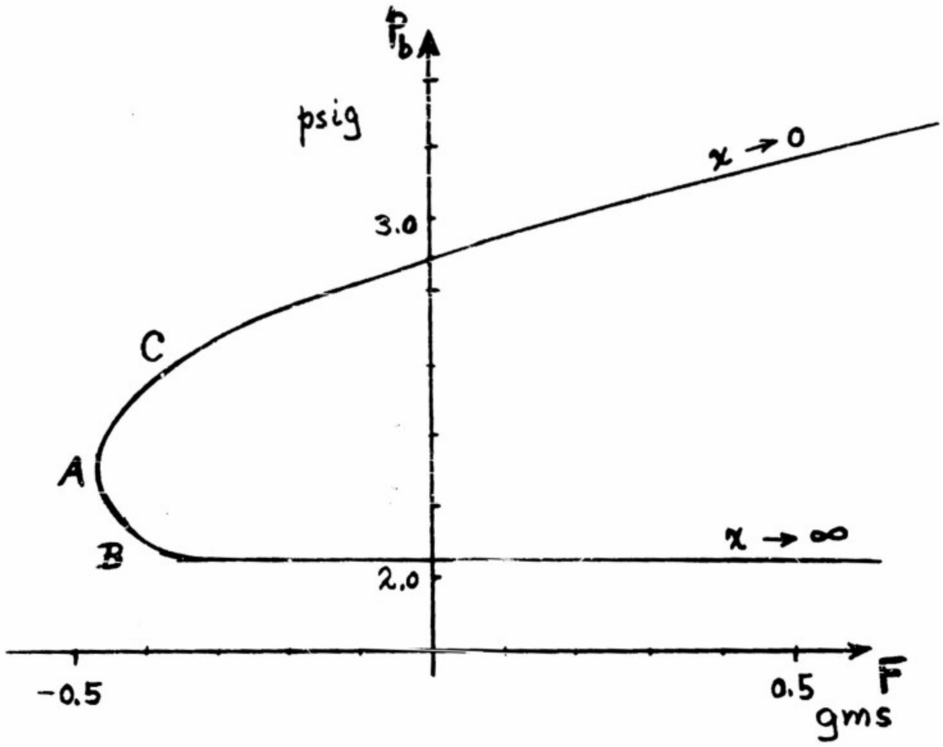
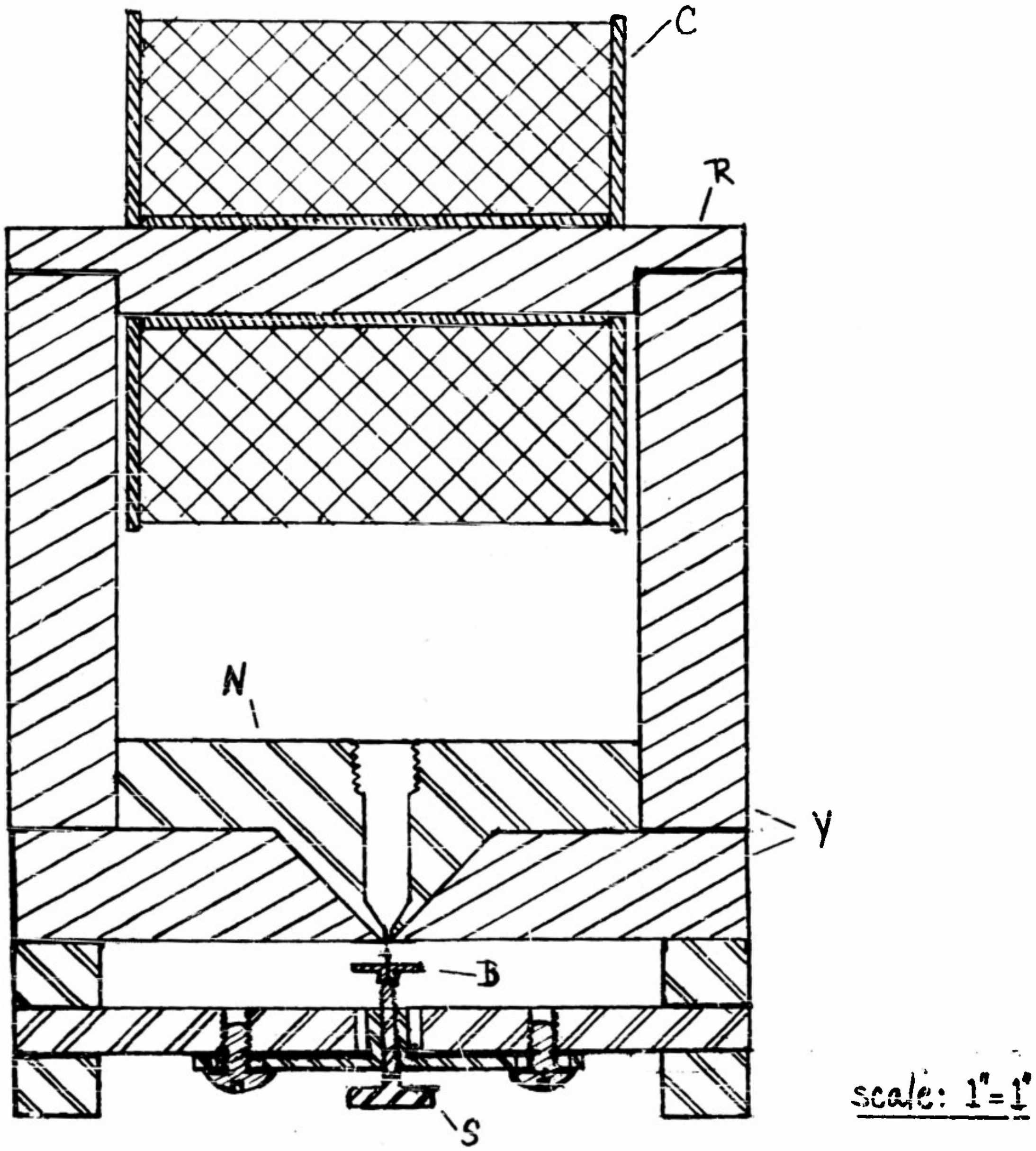


Fig. 1. Typical Force-Pressure Curve.

Two models, designated Mark I and Mark II, of electric meter movement were built and tested as adaptations of the flat-baffle force-pressure transducer to measurement of small currents. Both are of the moving-iron type and are very much the same, except that Mark II features more carefully treated iron and better geometry in the magnetic circuit, and a specially-wound coil. Fig. 2 is a drawing of Mark II.

Because delivery of the special coil was delayed for so long, a preliminary test was made with the Mark II meter, using a coil of 120 turns. With 0.2 amperes, or 24 ampere-turns, a pressure change of 5.1 ins. Hg was observed, supply pressure being 10 psi. This is a sensitivity of 2.9 ins. H_2O per ampere-turn. After the 215,000-turn coil was finally received, we were unable in the time available to duplicate this sensitivity at low current, within a factor of the order of ten--i.e., our best sensitivity was more like 0.3 ins. H_2O per ampere-turn. The discrepancy can doubtless be ascribed to the following two factors:

1. The first measurements (with the 120-turn coil) were made on a half-bridge--the nozzle in series with an orifice, with gauge pressure being read on a vertical mercury manometer connected between orifice and nozzle. The later measurements were made on a full bridge, as shown in Fig. 3. The sensitive differential manometer was difficult to keep on a fixed scale position by adjustment of the valves V_1 and V_2, and consequently estimates of deflection due to electric current were rather badly masked by manometer drift.
2. The iron in the magnetic path had been subjected to 24 ampere-turns in the preliminary test. Subsequent demagnetization with alternating current of diminishing magnitude was not carried out to less than 1 ampere-turn. Hence it is probable that in the later tests the iron was not of as high initial permeability as



C -- coil of 215,000 turns; 130,000 ohms; No. 40 wire
R -- magnet core rod, 0.5" diam. } Armco Magnetic Ingot Iron,
Y -- magnet yoke, 0.5" x 0.625" } nitrogen-annealed
B -- baffle, 0.375" diam } (0.010" diam. stainless steel centering pin on baffle)
N -- brass nozzle structure, tapped for air connection, with 0.025" diam. nozzle opening
S -- screw for adjusting nozzle-baffle separation

Fig. 2. Construction of Mark II Meter.

in the first tests, immediately after heat treatment.

It is clear that both these limitations could be overcome by more careful, extensive work. Incentive for such work remains weak, however, until there is clearer evidence that electric current measurement is a useful direction in which to apply pneumatic force measurement.

<u>Other Configurations</u>. In addition to the single flat-nozzle, flat-baffle configuration, a number of other geometrical arrangements were considered. These included arrays with two nozzles more or less opposed to each other, devices in which the baffle motion was across the jet axis instead of along it, and various shapes of curved nozzles or baffles. So far as the general problem is concerned, of finding optimum designs for pneumatic force-pressure transducers, we feel that we have barely scratched the surface. The possibilities to be tried are practically endless, so a good theoretical critique is invaluable. Since the flat geometry was the only one into which we had a reasonable theoretical insight, no other configuration was given systematic study.

The most interesting and promising of these subsidiary experiments featured the pointer of an ordinary panel microammeter movement, mounted beneath a conical nozzle so that pointer movement was across the jet axis. See Fig. 4. This simple sketch does not fully disclose the exact aerodynamic shape of the pointer tip, which in the broad, heart-shaped portion has a slight downward curvature toward the edges. Also the ridge of the stem portion extends somewhat into the heart-shaped portion. These details are probably much less important than the exact shape of the tip, since the nozzle was mounted above the narrowing tip portion.

By careful adjustment of the vertical separation between nozzle and pointer tip to a very small value (not accurately measured), and with an air supply pressure of only 0.5 psi, application of 0.5 μa gave pressure change corresponding to sensitivity of 0.024 psi mg^{-1}. This was with a full

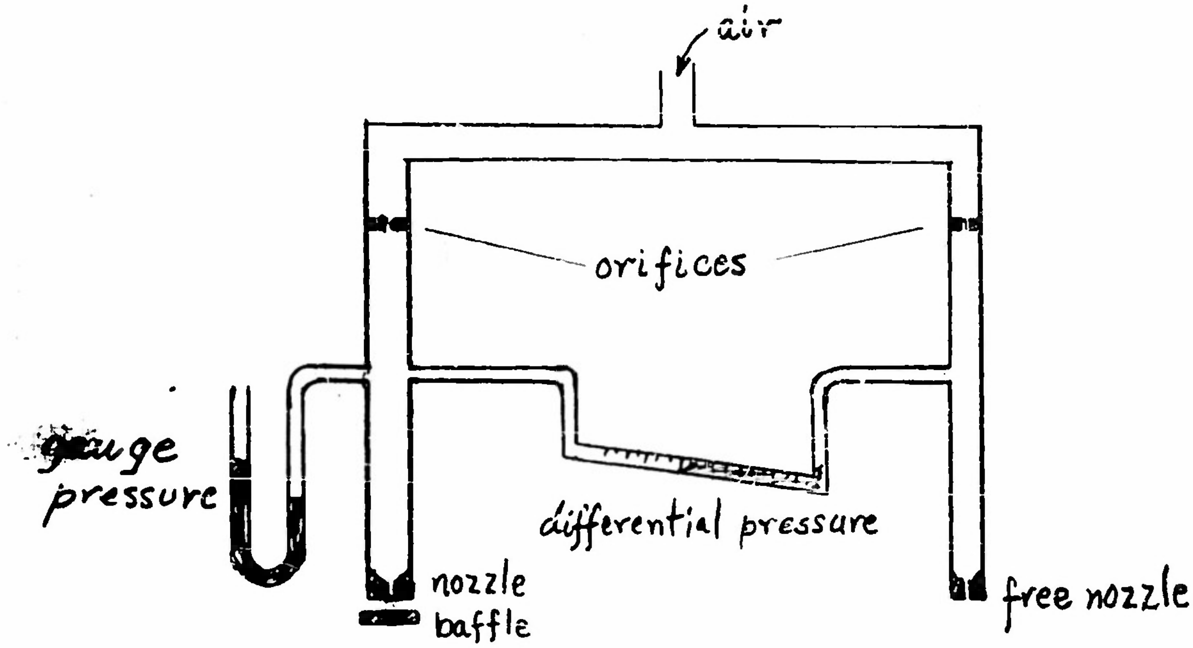


Fig. 3. Full Pneumatic Bridge.

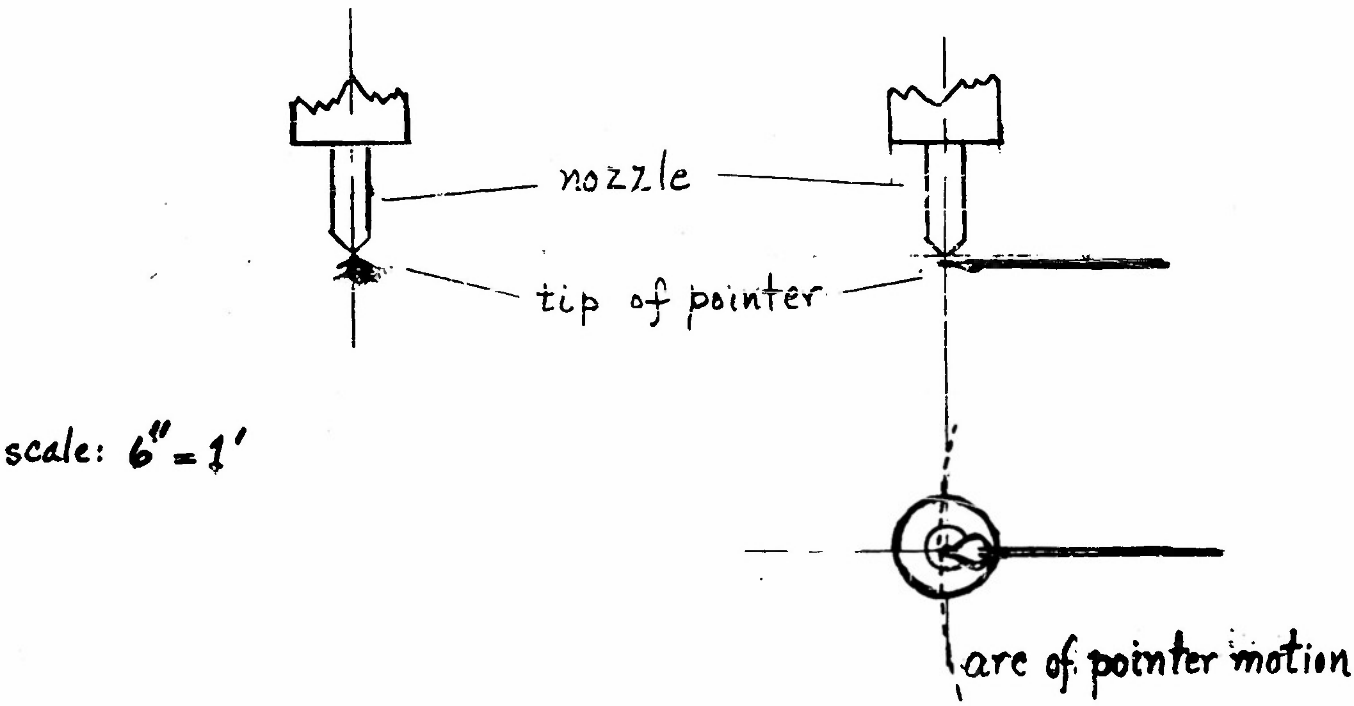


Fig. 4. System with Transverse Baffle Motion.

pneumatic bridge with 0.0135" diameter orifices and with differential pressure read on an inclined manometer.

Conclusions as to Force Measurement. Though the work described in this report is far from exhaustive, we do feel that the possibilities of pneumatic force-pressure transducers have been investigated to the point where pros and cons may be tentatively summarized.

In favor of further development of such transducers, it may be said that by straightforward procedure (use of commercially available pressure regulators, valves, manometers) and a small amount of fine machine work (drilling of orifices and nozzles, fabrication and suspension of baffle) it is possible to demonstrate fast and reasonably accurate measurement of forces in the milligram range. Since this result was established with a relatively small effort, it seems reasonable to expect that a more careful, prolonged study would yield noticeably superior performance.

The principal difficulty revealed by our work is the general problem of baffle suspension. Ideally, this should be frictionless, independent of orientation with respect to gravity, and permitting easy application of the force to be measured. The nature and importance of these requirements will vary with the type of measured force. Permanent vertical orientation would not be unduly restrictive for laboratory weighing but would be intolerable in a portable electric meter. Vertical orientation permits aerodynamic suspension within certain limits of total weight. For example, in our flat-baffle experiments the baffle weight of about 0.5 gm was supported against gravity by the Bernoulli attraction. For weighing milligram quantities of most materials it would not be unreasonable to keep the balance pan weight below 0.5 gm.

Even with aerodynamic suspension there may be need for guide pins or other stops to limit lateral motion of the baffle, and thus some danger of sticking friction. It may be possible to provide lateral stability by

aerodynamic forces as, for example, with a spherical ball (baffle) inside an inverted conical funnel (nozzle).

For applications where permanent vertical orientation is not acceptable, various forms of pivoted or elastic suspensions may be considered. Since the necessary displacements are very small, purely elastic suspension seems useful. For measuring very small forces, the spring stiffness of the elastic suspension must be correspondingly small. Further, the suspension must provide highly accurate positioning of the baffle relative to the nozzle. Requirements appear, however, to be within the abilities of modern instrument-making art.

Conclusions on Portable Radiation Detectors. Typical portable radiation detector specifications call for full-scale ranges of 0.25 up to 500 roentgens per hour. This corresponds, in one gram of air, to currents of 1.8×10^{-11} up to 3.6×10^{-8} amp. So one might say that currents to be measured are in the general range of hundreds of micromicroamperes. The Model RT Ohmart cell, for example, is described by the manufacturer as generating 1×10^{-12} amp for 1 mr hr^{-1} from a Co-60 source. To be useful, a batteryless detector operating from such a cell would therefore need to furnish readings of currents as small as some 10^{-10} amp. This is two orders of magnitude below the best sensitivity we demonstrated (5×10^{-8} amp) with a complete pneumatic meter. However, as mentioned in preceding sections, we concentrated more on force measurement than on current measurement.

In addition to the problem of sensitivity, which is important both in laboratory and in portable instruments, the requirement of portability imposes other requirements. Our experiments on pneumatic force measurement with the flat-baffle system required pressure-regulated air flows of the order of 20 std. cm^3 sec^{-1}. Provision of this flow in a portable, manually-pumped system would be a formidable problem. However, the transverse-motion

baffle gave promising results with only 0.5 psig pressure supply (compared to 10 psig for the flat baffle) and correspondingly smaller flow (not measured), so that the portability requirement is much less severe.

In summary, the three requirements of sensitivity, stability, and portability proved to be more than we could meet in a finished, complete portable radiac with indirect pneumatic indication. We would consider it premature to say that these requirements could not possibly be met, particularly if the promise of the transverse baffle experiment is not illusory.

V. Radiation Detection by Direct Pneumatic Effect.

The full picture of the interaction of radiation with matter is quite complex. Ionization and photoelectric effect are doubtless the two actions most generally important for radiation measurement. In looking for possible direct effects of radiation on pneumatic parameters it is therefore natural to start with ionization of gases. In fact, practically all the possibilities we have considered are based on ionization as the fundamental process. The work to be reported here is entirely of a survey nature. None of the possibilities was reduced to practice. The following presentation gives first some general energy considerations and then a brief discussion of the more interesting avenues of development that appear to be open. This section may be summarized in the statement that direct pneumatic effects of radiation constitute an area of some general interest, though not resulting at this time in any concrete proposal meeting portability requirements.

Energy Considerations. Every indicating instrument converts an "input" energy change, representing some interference with the measured quantity, into an "output" energy change, associated with an observable scale reading. This conversion may or may not include power amplification, depending on the input power level compared to the desired speed of response

and energy level of output indication. For radiation detectors the input power is that delivered by radiation absorbed in the instrument.

The "average" input power level of radiation detectors may be taken as the 83 erg hr^{-1} corresponding to 1 roentgen hr^{-1}, or 0.023 erg sec^{-1}. For comparison with this power level, we may take the energy stored in full-scale deflection of a panel microammeter (Simpson Model 26, 25 microamp., our Code No. A-101; cf. p. 9, ref. 1). With a spring rate of 7.33 erg rad^{-2} and full scale deflection of 1.75 radians, the energy is 11 ergs. In addition there is the I^2R loss in the 2100-ohm coil, which amounts to 13 erg sec^{-1}. This comparison shows clearly the power amplification needed for this kind of indication.

The ultimate low level of powerrequired for indication would be represented by the spinthariscope used with a fully dark-adapted eye. A 1 mev particle converted at full efficiency would give some 5×10^5 photons, of which only about 7 would be needed for the eye to see. Even allowing for very low efficiency, it would seem probable that each "counted" particle would give a visible indication. So this is an example requiring no power amplification.

It is interesting to compare scintillations, visible only in the dark, with cloud chamber tracks, visible only under good illumination. Both are directly (i.e., without further amplification) visible, but it must be noted that the track occurs only because of energy previously stored in the supersaturated vapor. Thus the cloud chamber involves a kind of (discontinuous) power amplification.

For a portable radiation meter the requirement must be met of readability under ordinary ambient illumination. The foregoing examples suggest that this can be accomplished only by provision of power amplification of the order of 500.

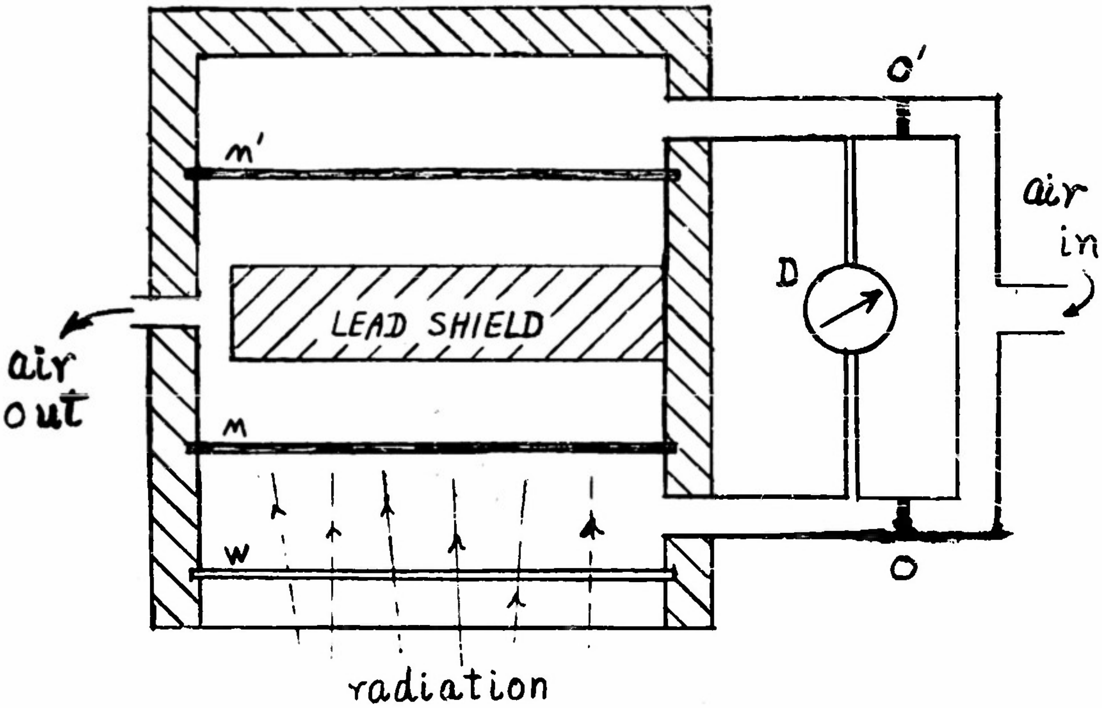
During the course of this project some cursory thought was given to

a considerable variety of ideas for radiation detection. Requirements of portability, manual (battery-less) operation, and limitation to pneumatic effects, reduced the number considered to fall within the scope of the project; and energy considerations served further to eliminate all but the relatively few ideas developed in this report.

The Viscosity Bridge. One mechanism by which radiation might conceivably affect a pneumatic system would be by changing viscosity of the gas. Sufficiently sensitive measurement of differential pressure drop across two porous membranes, identical except that only one is subject to radiation, might serve for radiation detection. This idea was tested in the form of a viscosity bridge, sketched in Fig. 5. Only a limited test of this device was carried out, principally because of the hazards in using the polonium source. (The method of clamping the source in place was not carefully enough worked out, and the protective film was broken.) It was planned to test both metallic and non-metallic porous diaphragms. Only the non-metallic (Corning fritted glass) were tested.

With supply pressures up to 20 psig and with a wide range of porosity of the glass diaphragms, no detectable effect was found. Since the non-metallic discs seemed a priori more favorable, there was little incentive to use the limited available time for further testing of this approach.

Studies(5)(6) are available which show that the average ion density to be expected would be no more than 10^3 ions cm^{-3} per disintegration, with spacing such as we had--about 1 inch. Our source, furnished as 35 millicurie, presumably furnished in the half space some 10^8 disintegrations per second. With the geometry and flow rates of the viscosity bridge, this puts an upper limit of some 10^{11} ions cm^{-3} for the air flowing through the irradiated membrane. Since there are in standard air 2.7×10^{19} molecules cm^{-3}, the relative ion density could scarcely be more than one in 10^8.



O,O' -- orifices
M,M' -- porous membranes
D -- differential pressure gauge
W -- window to admit radiation

Fig. 5. Diagram of Viscosity Bridge.

The effect per ion on viscosity may be estimated from theoretical and experimental consideration of ion mobility. At given temperature the mobility is proportional to the mean free path, λ_i, of the ion in the gas. At given pressure and temperature, viscosity is proportional to mean free path. Hence the effect per ion on viscosity would be determined by the value λ_i relative to λ_g, the mean free path of neutral gas molecules. The example of oxygen(7) suggests that λ_i is something like half of λ_g. Hence the ions would have a relative weight of about two in the direction of diminishing the viscosity coefficient. This factor of two does not go far toward overcoming the low relative ion density deduced in the preceding paragraph.

There is perhaps some chance that a porous membrane material might be found that would itself be subject to some radiation effect which would interact cumulatively with ionization of the gas so as to give a larger apparent change of viscosity. This would not be, strictly speaking, a pneumatic effect; and, in summary, one must say that the effect of radiation on viscosity does not seem a promising direction in which to look for a useful direct pneumatic effect.

Cloud Chamber Devices. If one broadens the concept of pneumatic effects to include condensation and evaporation, the cloud chamber may be regarded as a possible means of exhibiting directly the effect of radiation.

For example, a commercially available piece of demonstration apparatus (Cenco-Knipp Alpha Ray Track Apparatus, Cenco Catalog No. 71245) provides the pattern for a possible radiation detector. This device is simply a small, manually-operated cloud chamber, with a speck of alpha-emitter permanently mounted to one side. Replacement of this known emitter by a sample to be counted would permit at least crude measurement by visual observation of the number of tracks. It is true that a direct

voltage of 100 to 200 volts must be supplied to this apparatus to sweep charged particles from previous expansions out of the way, and so it does not entirely represent a manually-operated instrument. But more fundamental than this is the limitation that visual estimate of track numbers (or other factors such as number, size, rate of fall of droplets) does not constitute a good basis for quantitative measurement. Photoelectric conversion to a meter reading is possible for some effects[8][9].

One might hope to achieve quantitative indication from the cloud chamber effect by a differential arrangement of two chambers, with only one subject to radiation. Thus we postulate two identical chambers, except that in one a certain extra condensation takes place upon expansion because of the ionization left by radiation. This extra condensation has two effects[10]: a reduction of vapor pressure (and, to that extent, of total pressure) and an increase of temperature, due to heat released by condensation of vapor. Thus measurement either of differential pressure or differential temperature between the two chambers might serve as indication of radiation.

Unfortunately, the pressure and temperature effects appear to interfere substractively rather than additively. However, a more careful study, both theoretical and experimental, of the time-dependence and magnitude of temperature and pressure changes is needed before the true potentialities of this approach can be estimated. Such a study would seem to be of basic value to understanding the cloud chamber in many of its applications.

Measurement of pressure or temperature has the advantage over any visual observations of tracks that it averages, more or less instantaneously,

over the whole chamber volume, and thus does not reflect just a localized radiation effect.

VI. Conclusions

Work supported by this Project may be continued in The University of Tennessee Physics Department along two lines: (1) exploitation of pneumatic measurement of small forces; (2) response of the human eye to time-dependent visual stimuli, particularly relating to intensity and to polarization. Emphasis given to the first will naturally depend largely on the outcome of the patent search, since it would be predominantly an industrial development. Emphasis on the second will reflect a long-range interest of Department staff members.

It is also our hope that investigators at other universities and research establishments may find in the work we have reported the beginnings of worthwhile further effort.

Appendix

Theory of Flat-Nozzle Flat-Baffle Transducer

The general principle of this device may be explained with reference to Fig. 6. Incoming air from a pressure-regulated supply flows first through a fixed orifice and then through the nozzle and along the movable baffle to the atmosphere. Under these conditions the back pressure p_b will be a sensitive function of the separation x. The force required to maintain the baffle at a particular separation and the relation of this force to the measured back-pressure are the objects of this study. In particular, an effort is made to predict the force-separation curve. This is a semi-empirical treatment, with primary emphasis on observed experimental results.

The observed relationship of force and back-pressure has already been displayed in Fig. 1. The problem now is to analyze this overall relation into its two components: the relation of force F to separation x; and the relation of back-pressure p_b to separation x.

If the symbols p_s and p_b represent gauge pressures and if Q represents volume velocity of flow, it seems reasonable to represent the pressure drops across the orifice and the nozzle-baffle by the equations:

$$p_s - p_b = k_o Q^n \tag{1}$$

$$p_b = k_n Q^n \tag{2}$$

in which k_o and k_n are resistance coefficients of the orifice and of the nozzle-baffle configuration respectively. The latter naturally depends on the separation, so that

$$k_n = k_n(x) \tag{3}$$

Eliminating Q from (1) and (2), we have

$$\frac{p_b}{p_s} = \frac{1}{1 + (k_o/k_n)} \tag{4}$$

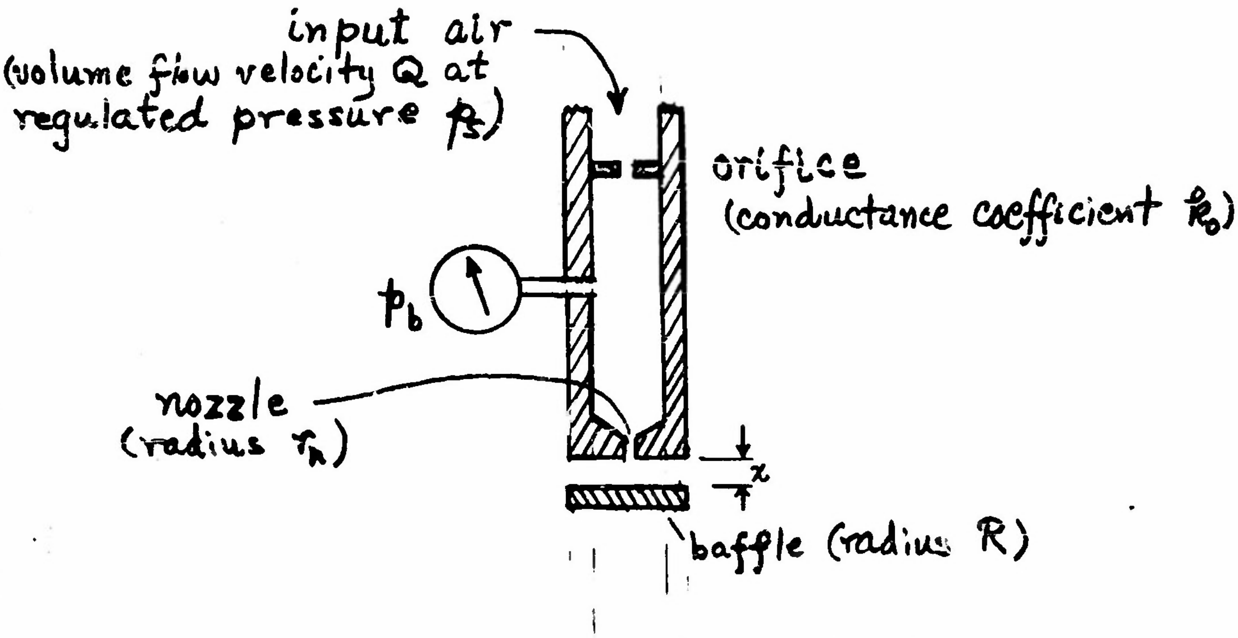


Fig. 6. Cross-section Diagram of Flat-plate Transducer.

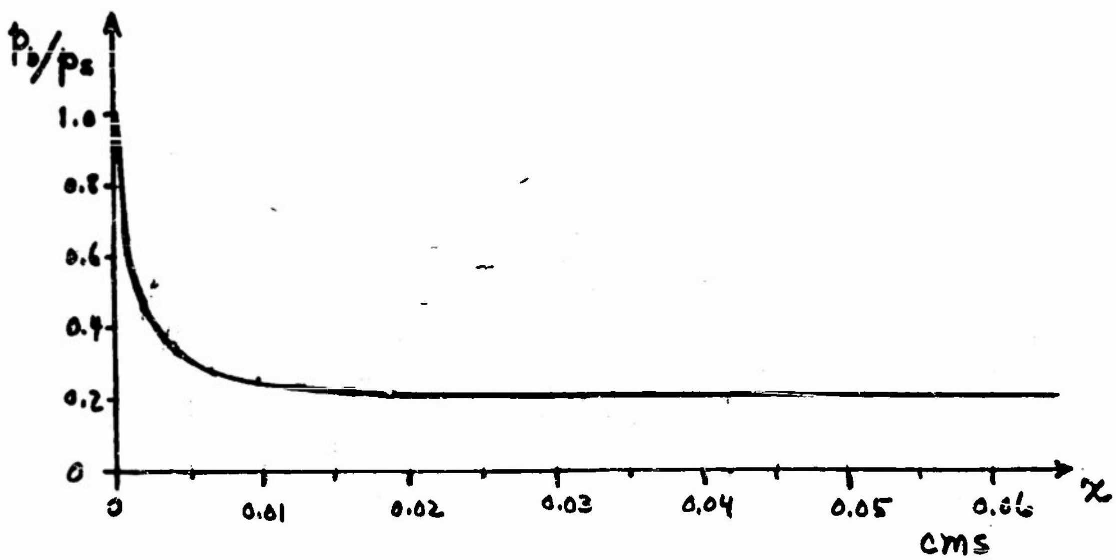


Fig. 7. Observed Pressure-separation Dependence.

or conversely,

$$\frac{k_n}{k_o} = \frac{p_b/p_s}{1-(p_b/p_s)} \tag{5}$$

The observed dependence of p_b/p_s on separation x is as shown in Fig. 7. The corresponding dependence of k_n/k_o, according to Eq. (5), is given in Fig. 8. Using this as basis, one can attempt to replace Eq. (3) by a specific formula. The form suggested by Fig. 8 is

$$\frac{k_n}{k_o} = k_{no}\left(1 + \frac{B}{x^m}\right) \tag{6}$$

(No great effort was put into fitting a formula to the curve of Fig. 8--all that is needed is something that will illustrate the further procedure.)

Let F denote the force on the baffle and let F^* denote the approximation to the force which might be achieved by neglecting viscosity. Then F^* would involve two terms: a downward force representing rate of change of momentum, and an upward force due to Bernoulli effect. Thus:

$$F^* = \rho Q\left(\frac{Q}{A_n}\right) - \int_{r_n}^{R}\left(\frac{1}{2}\rho v^2\right) \cdot 2\pi r dn \tag{7}$$

where ρ is density (assumed constant, Mach numbers being no more than one-third), and $A_n = \pi r_n^2$.

Substituting $v = Q/2\pi rx$ into Eq. (7) and integrating yields

$$F^* = \rho Q^2\left(\frac{1}{A_n} - \frac{\ln(R/r_n)}{4\pi x^2}\right) \tag{8}$$

If n = 2 in Eqs. (1) and (2), then

$$Q^2 = \frac{p_s}{k_o + k_n} \tag{9}$$

and Eq. (8) becomes

$$F^* = \frac{\rho p_s}{k_o + k_n}\left(\frac{1}{A_n} - \frac{\ln(R/r_n)}{4\pi x^2}\right) \tag{10}$$

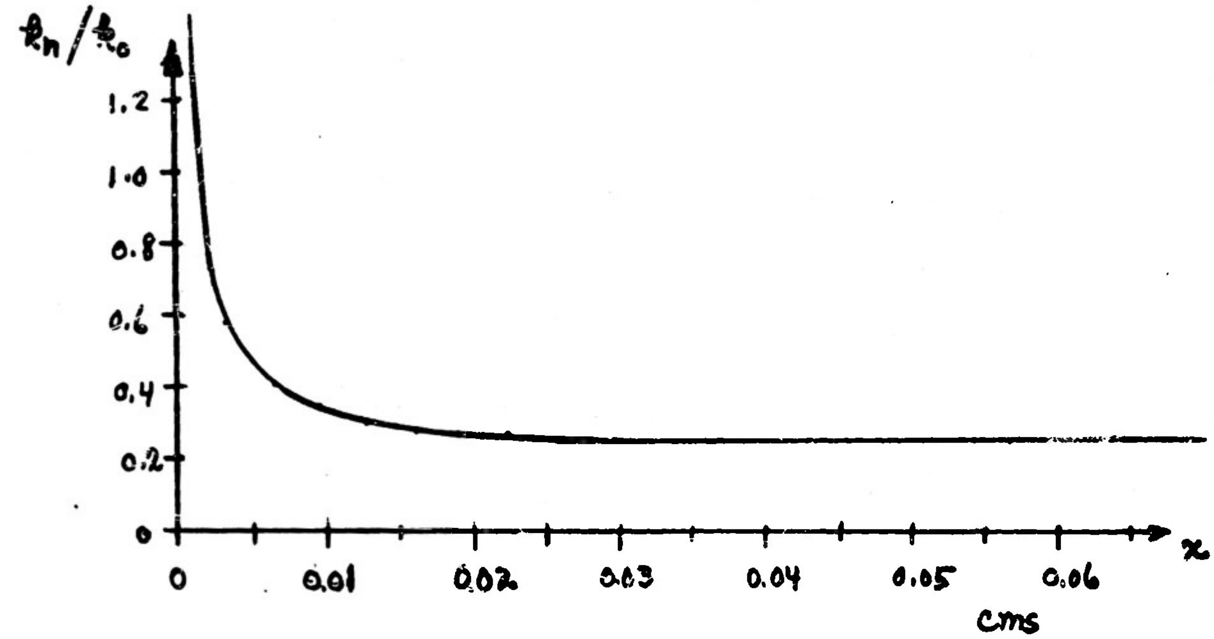


Fig. 8. Hypothetical Nozzle-Coefficient Dependence on Separation.

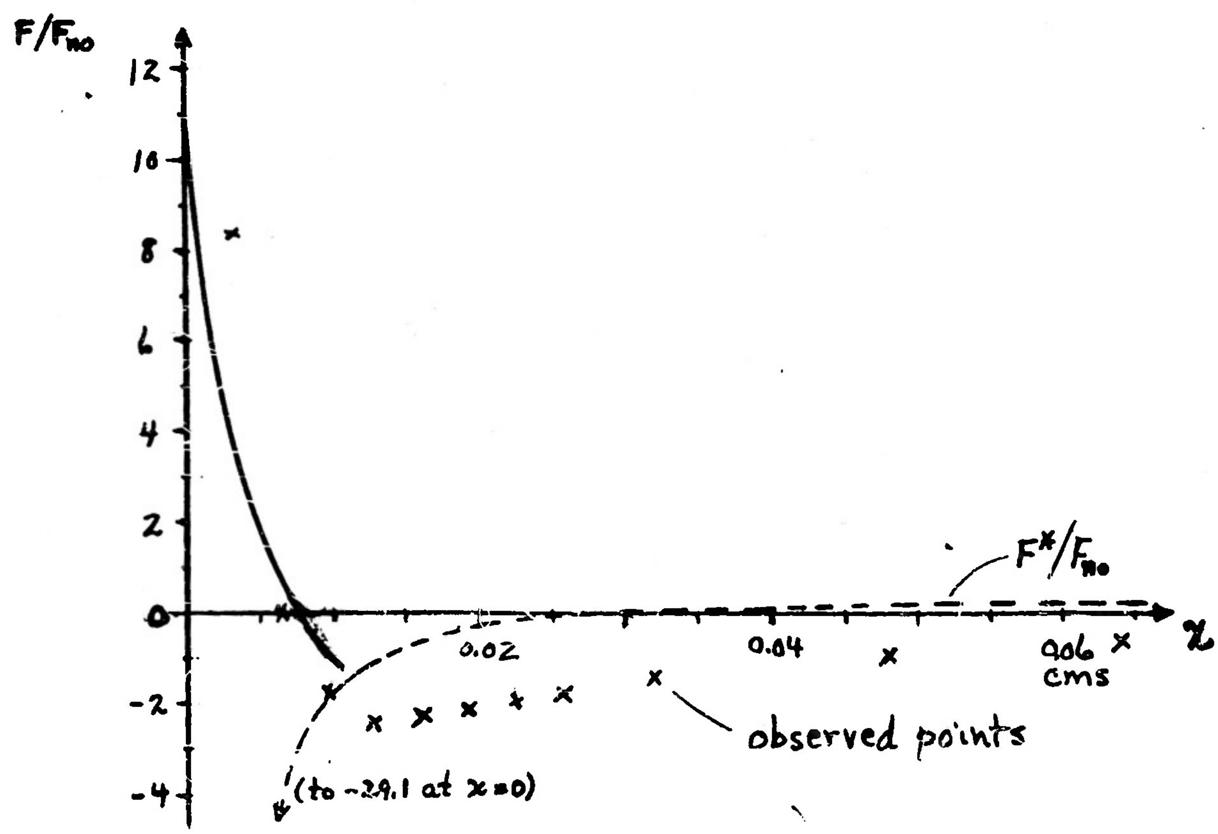


Fig. 9. Theoretical and Observed Force vs. Separation.

Define

$$F_{no} = \frac{\rho p_s}{k_o A_n} \tag{11}$$

This is the force which momentum change would exert if through A_n issued the full volume flow $(p_s/k_o)^{1/2}$ which p_s could force through the orifice alone. Introducing F_{no} and k_n from Eq. (6), into Eq. (10) gives

$$\frac{F^*}{F_{no}} = \frac{x^m}{(1+k_{no})x^m + Bk_{no}}\left[1 - \frac{A_n \ln(R/r_n)}{4\pi x^2}\right] \tag{12}$$

This is used in plotting the broken curve of Fig. 9, with $m = 2$, $B = 10^{-5}$ cm^2, and $k_{no} = 2.60$. Since viscosity was neglected in deriving Eq. (12), it is to be expected that the total force F will differ from F^*, and that the difference will approach, at $x = 0$, a positive (repulsive) force of magnitude $A_n p_s$. The solid curve of Fig. 9 is an estimate of the way this correction might add to the other effects.

A typical set of observed values of F vs. x are also plotted on Fig. 9. Many such measurements were made, for various values of p_s and for different orifice and nozzle combinations. Measurements were made by supporting the baffle on one arm of an analytical balance for force measurement. Separation was measured by an optical lever working from the cross-beam of the balance. (The set-up used for these measurements differs from that of Fig. 6 in that the baffle and nozzle were not of the same diameter--the nozzle was of 5/16 in. diameter and the baffle was 1 1/4 in. in diameter. See discussion of numerical values below.)

Although the agreement between theory and experiment displayed in Fig. 9 is not impressive, it is about what can be expected from the derivation of Eq. (12) and from the gross estimate of viscosity effects. The important point is that the shape of the force-separation curve was correctly guessed à priori, then determined experimentally, and finally understood at least

qualitatively from the theoretical side.

Numerical values used for Fig. 9 are as follows: $r_n = 0.0125$ in., $\ln(R/r_n) = 3.0$, $\rho = 1.2 \times 10^{-3}$ gm.cm^{-3}, $p_s = 6.89 \times 10^5$ dyne cm^{-2}. This gives $F_{no} = 198$ dynes, $A_n p_s = 2.18 \times 10^3$ dynes, corresponding at $x = 0$ to $(A_n p_s/F_{no}) = 11.0$. The value of $\ln(R/r_n)$ is a guess as to the proper value to represent the large baffle diameter, but the choice is not sensitive--baffle diameter ranging from 3/8 in. to 1 1/4 in. gives $\ln(R/r_n)$ ranging from 2.71 to 3.91.

In review of the entire effort represented by this appendix, it appears that better theoretical interpretation of experimental results would call for two kinds of improvement over our work: (1) improved measurement, particularly more systematic measurement of flow rates; and (2) more careful theoretical approach to such matters as the assumptions basic to Eqs. (1) and (2).

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